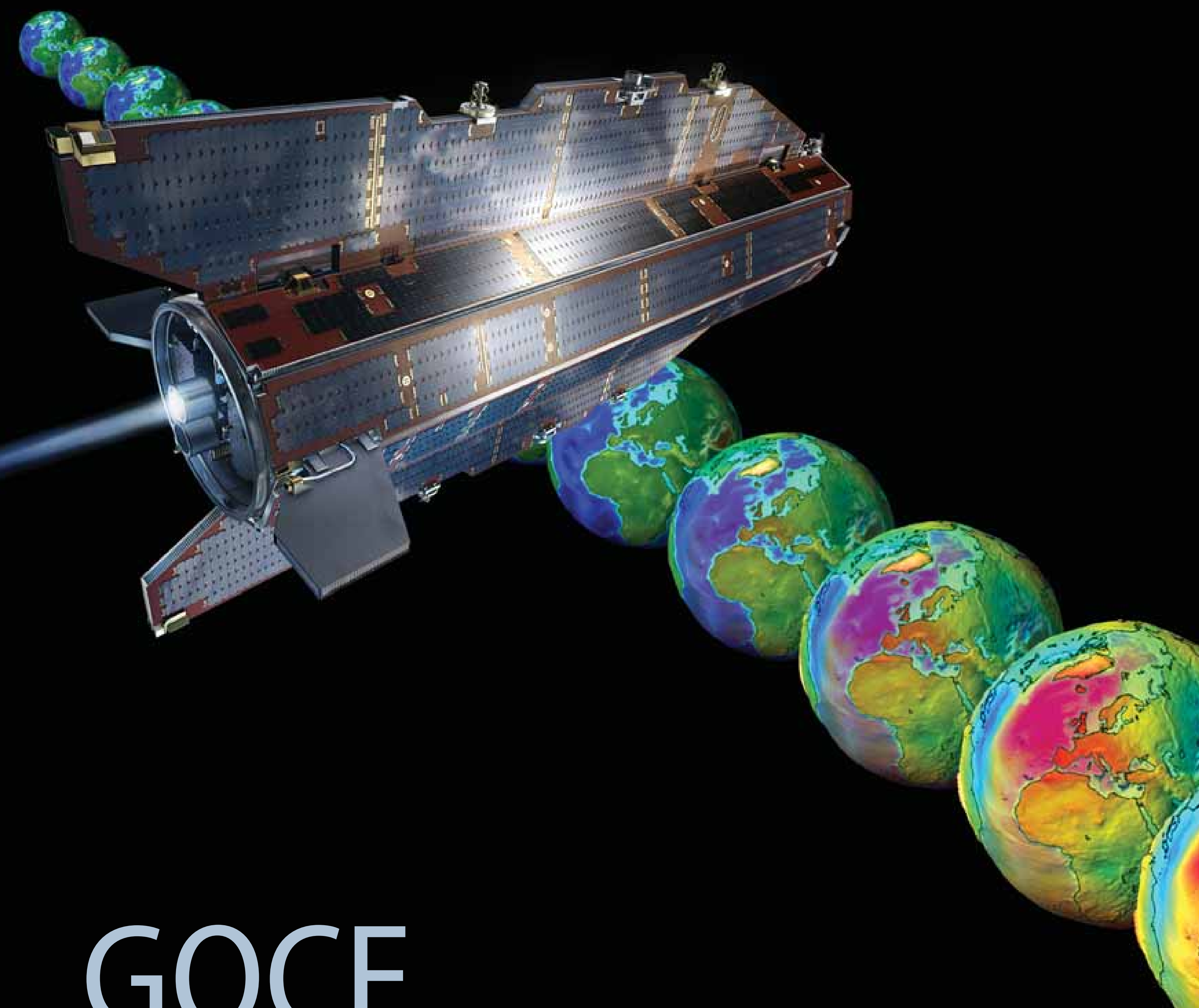
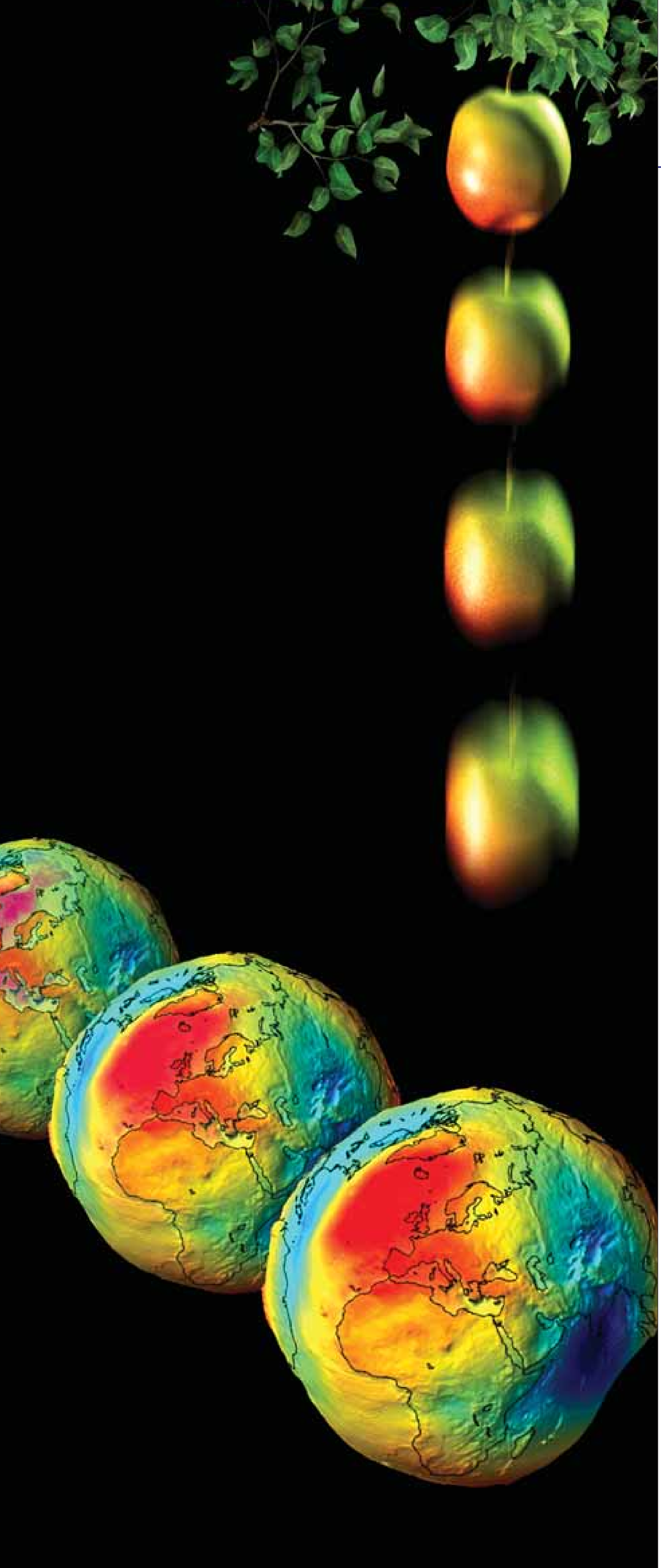


GOCE

Obtaining a Portrait of Earth's Most Intimate Features



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Known as ESA's 'Gravity Mission', GOCE represents a blend of revolutionary new technology, designed to open a new chapter in what has historically been one of the most intriguing issues confronting science. Scheduled for launch in mid-2008, GOCE will deliver data about the fundamental force of nature, which will benefit a broad range of applications in Earth sciences.

Introduction

The Gravity field and steady-state Ocean Circulation Explorer (GOCE) is the first core mission in a series of six approved ESA Earth Explorers. GOCE embodies many firsts in terms of addressing the shape and characteristics of Earth's gravity field in unprecedented detail.

Although invisible, gravity is a fundamental and complex force of nature that has an immeasurable impact on our everyday lives. Gravity varies in an extremely subtle way from place to place on the surface of Earth and in space, due to a number of factors such as Earth's rotation, position of land masses, variations in the density of Earth and the redistribution of mass

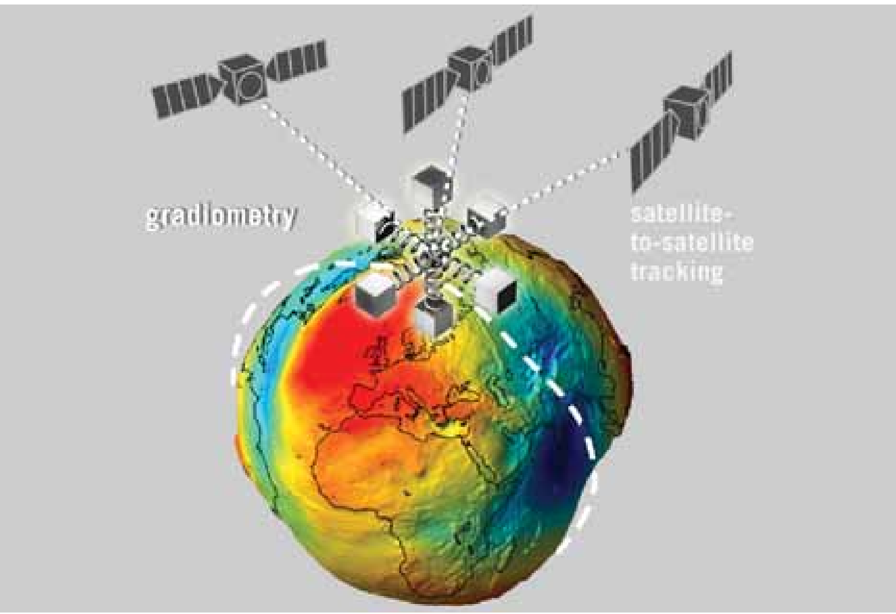


Illustration of GOCE concept, illustrating the gravity gradiometer sensor measurement principle and the high-low GPS satellite positioning as the satellite circles the geoid (AOES Medialab)

due to effects such as motions of the gaseous, fluid, or solid components of the Earth system.

A better knowledge of the gravity field is needed to provide more insight into Earth's interior, while a precise model of the geoid (a level surface defined by equal gravitational potential) as defined by the gravity field, is crucial to understanding more about ocean circulation.

The challenge of observing gravity is complicated by the fact that the average observable signal at the surface depends closely on the scale at which we wish to resolve details. The magnitude of the signal decays rapidly, considering the effects from large features to small ones (see Components of Earth's gravity). This makes it difficult to distinguish small-scale features in the presence of the primary terms of the gravity field.

The problem of measuring effects of local variations in gravity is further compounded by the fact that at satellite altitudes the scale-dependent signal is rapidly attenuated with distance above Earth's surface. This makes it challenging to determine Earth's gravity field from space, and it is particularly difficult to resolve small-scale features. Therefore, it is imperative to fly in an orbit as low as is technologically feasible and to find a measurement technique to further counteract the altitude-dependent attenuation of gravity.

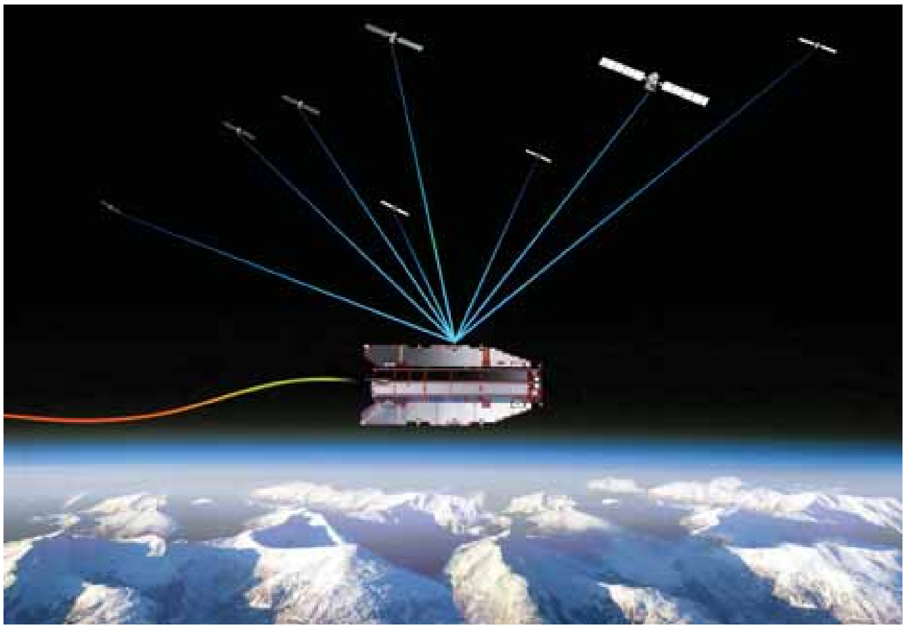
Principles of the Satellite Gravity Mission

Satellites in orbit behave according to the physics of Newtonian mechanics. GOCE, specifically designed for the purpose of measurement of Earth's gravity field, will be launched into a Sun-synchronous near-circular orbit and will travel with a speed of around 8 km/s in order to remain in 'free fall'. The orbit will typically be inclined at several degrees off the pole such that Earth's equatorial bulge acts to rotate the plane of the orbit around Earth, at a rate that matches the motion of the Sun across the sky. The orbit will also be tuned to optimise the sampling pattern over certain intervals of time.

In this configuration, the basic ingredients required for a high-precision gravity mission are:

– global coverage with data of homogeneous quality;
– a gravity sensor based on the concept of a gravity gradiometer;
– a low orbit with accurate positioning and precise orbit determination by means of a Global Navigation Satellite System (GNSS);
– the effects of non-gravitational forces to be measured and/or compensated for;
– instruments providing knowledge of the orientation of the gravity sensor in space;

GPS satellite tracking is used to accurately determine the location of the spacecraft in its low Earth orbit, and the large-scale undulations in the satellite orbit trajectory in response to the gravity field (AOES Medialab)



Components of Earth's Gravity

The primary constituents of gravity

The acceleration that a body experiences because of gravitation when it falls freely close to the surface of a massive body, such as planet Earth, is known as the acceleration of freefall. The value of gravity *g* experienced directly at the surface of Earth approximates to 9.8 m/s^2, though the exact value depends on location. The primary contributions to *g* depend on several factors: the effects of a spherical Earth is of order one, while that caused by Earth's rotation and equatorial bulge is of order 10^{-3} *g*; mountains and ocean trenches result in the next largest constituent of order 10^{-4} *g*; and further deviations of the actual field from an ellipsoidal model, together with internal mass distribution and other factors, result in variations the order of 10^{-5} *g* or less.

- ability to correct the signal contribution due to orbital rotation of the sensor;
- minimisation of self-gravitational forces, or signal contamination due to local platform noise.

In order to realise a precise measurement capability, the satellite together with its gravity sensor and system of supporting instrumentation and control elements, must be considered to form a single composite gravity-measuring device.

Mission Objectives

The GOCE single-satellite mission is dedicated to measuring Earth's gravity field and providing a model of the geoid with unprecedented accuracy and spatial resolution. The scientific community proposing the mission posed the primary challenges as measurement of Earth's gravity gradients in all spatial directions and accurate satellite orbit determination to an accuracy that will allow determination of:

- gravity field anomalies with an accuracy of 1 mGal (or 10^{-5} m/s^2),
- the geoid to an accuracy of 1–2 cm.

Both of these objectives should be met at a spatial resolution (i.e. half-wavelength scale) of 100 km or less with global, regular and dense measurements of high and homogeneous quality.

GOCE is the first satellite mission to employ the concept of gradiometry. Satellite gradiometry is the measurement of acceleration differences over short baselines between proof masses of an ensemble of accelerometers inside a satellite. The GOCE gravity gradiometer contains six proof masses, each capable of sensing detailed local changes in acceleration in three dimensions with extremely high precision. With its ultra-sensitive accelerometers, the gradiometer instrument is capable of providing effects of gravitational origin. In this way, the effect of the altitude-dependent attenuation of Earth's gravitational attraction is counteracted.

Although the gradiometer is highly accurate, by itself it is not able to map the complete gravity field at all space scales to the required accuracy. Thus to overcome this limitation, the position of the GOCE satellite is tracked by GNSS satellites at an altitude of 20 000 km – a concept known as 'high-to-low satellite-to-satellite tracking'. Analysis of the satellite motion in orbit yields gravity field information caused by large-scale phenomena. Complementary, the gradiometer is used to retrieve the high-resolution features of the gravity field.

The high spatial resolution achieved for the GOCE geoid model product is essential for the determination of stationary ocean dynamic topography in general, and particularly for high-resolution ocean circulation determination. In addition, its data will be useful for levelling by GPS, navigation, continental lithosphere studies and for global unification of height systems allowing, for instance, the establishment of a global sea-level monitoring system.

Benefits of GOCE Data

The GOCE mission will collect new data with which to make significant advances in the field of geodesy and surveying. These areas will benefit directly from the accurate gravity gradient products and the gravity and geoid model products derived from GOCE observations. These products will also be used to advance our knowledge of ocean circulation,

Parameter	**Requirement**		
	Accuracy	Resolution (km)	Spherical Harmonic Degree
Geoid (m)	0.01–0.02	100	200
Gravity Anomalies (mGal)	1.0	100	200

Modern local surveying tools, such as the spirit-level, simplify levelling on a small scale. But construction of early water-bearing structures, such as Roman aqueducts, relied on traditional levelling methods to transport water

which plays a crucial role in energy exchanges around the globe, sea-level change and Earth interior processes.

Land and Marine Surveying

The geoid is the classical reference surface for establishing physical levelling heights. It represents a surface along which no water flows from one point to another. Height systems on each continent and island are connected and unified in principle by placing a reference benchmark for each of them on the geoid. Unfortunately, this situation does not exist. Traditionally, the local reference benchmarks have been tied to local mean sea level, resulting in up to a few decimetres differences between them. The GOCE geoid is expected to allow unification of these systems on a global scale to within the resolution and accuracy of the model, which goes well beyond what exists today. This unification serves a number of purposes.

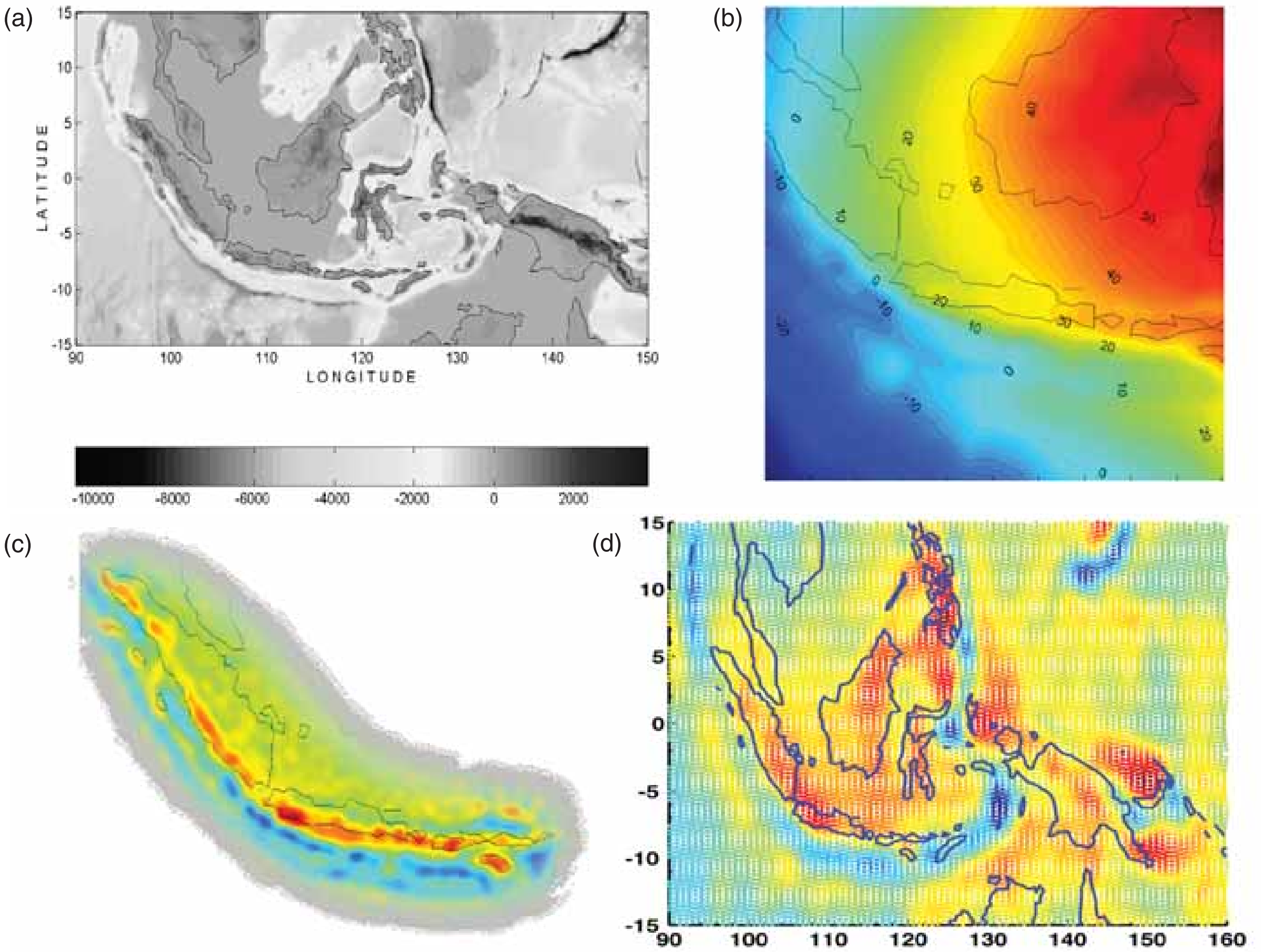
A unified height system would allow height systems to be connected across open water, such as lakes or ocean straits, easing tunnel or bridge construction projects. For example in the case of the Øresund bridge, crossing the Great Belt from Denmark to Sweden, there was a need to connect local height systems and to provide consistent and precise levelling over a distance of 22 km between the two countries. Such an application emphasises the need for precise topographic and gravimetric information. In addition, a unified height system would allow topographic height above sea level to be directly compared between for example the Mont Blanc in the Alps and Mount Everest in the Himalayas.

Furthermore, tide gauges basically recording locally relative sea-level changes can be made consistent with satellite altimetry data. The difference to the geoid allows a physical interpretation in terms of ocean dynamic topography and related currents.

Levelling versus GNSS Levelling

Classical levelling is an expensive and time-consuming field effort, and the user community would like to replace this

The Øresund bridge and tunnel system between Denmark and Sweden connected two national height systems



(a) Topography in the Indonesian archipelago; (b) global geopotential model of the region illustrating the coarse resolution, long-wavelength perspective offered by current satellite data; (c) in situ *and airborne data providing high-resolution perspective of the local details of the gravity field; (d) simulated GOCE gravity gradient measurements of the same region*

more traditional method by an indirect method. In a proposed new approach, GNSS geometric heights can be referenced to a geoid, from which physically meaningful levelling heights (known as 'orthometric heights') can be obtained. This requires a combination of the global geoid model from GOCE with regional gravity data to sufficiently small scales and with sufficient accuracy. In addition the GNSS height determination would need to be sufficiently accurate to be able to compete with the millimetre to centimetre accuracy of traditional levelling.

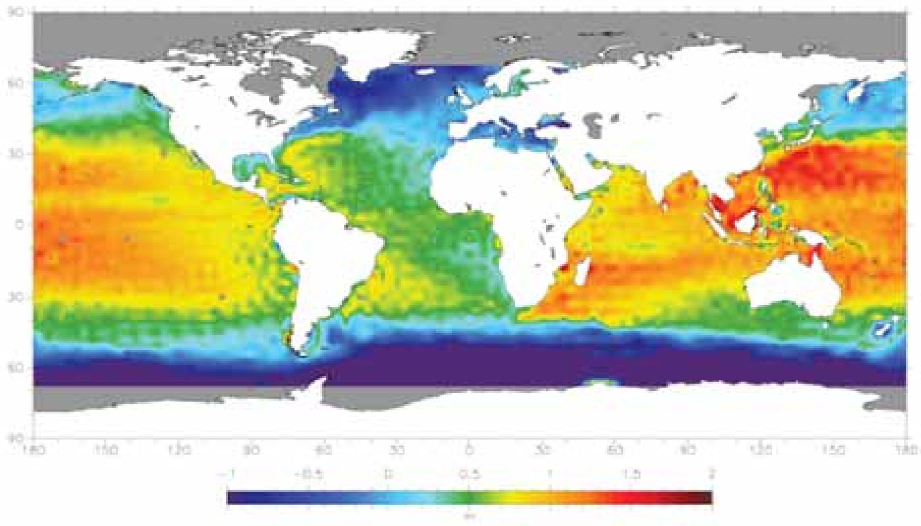
The same principle applies to the marine environment where GNSS-derived water-level heights of ships and depth-sounding data can apply the same geoid reference as the land data and the tide gauges. The instantaneous sea-surface topography data from the GNSS water-level heights from ships relative to the geoid can then potentially be used to feed and improve continental shelf or coastal ocean models. This would in the future require sufficiently accurate GNSS height determination and fast communication links for transmitting the results to aid the models. These applications will directly benefit from the availability of GPS, GLONASS and Galileo positioning systems in the future.

Solid Earth Physics

Combination of GOCE gravity field information and seismic data is expected to provide a detailed mapping of density variations in the Earth crust and the upper mantle, down to a depth of approximately 200 km. Satellite-derived gravity gradient data from GOCE will be especially useful for studies related to subduction zones where tectonic plates meet each other. Static density modelling and finite-element modelling can be used to study asperities in these subduction zones. New density models constrained by the GOCE satellite data will extend existing interpretations and provide new insight into frontier regions where little or no surface data exist. Examples are the relatively poorly understood regions such as Antarctica and the Himalayas.

A big advantage of GOCE data is that they provide global access to consistent gravity field information across all natural or artificial boundaries and, importantly, also in areas that are difficult to access. Methods need to be developed to fully exploit the potential of the new gradient data in geophysical applications. The resolving power of the satellite gravity information – potentially complemented with ground data – must also be quantified in order to ascertain the degree to which the satellite data resolve crust and mantle structures. The satellite and ground data can be compared to predictions from existing 3D density models that are currently based upon seismic and terrestrial gravity data. In addition, the satellite data can be tested against the gravity field predicted by independently determined density models that are based upon new petrologically and thermodynamically based methods. A highly accurate satellite data set from GOCE will also help to improve regional investigations (e.g. in the area of exploration geophysics) by providing a reliable and accurate boundary condition.

GOCE will also further our knowledge of land uplift due to post-glacial rebound by improving the initial value of the viscosity of the mantle. This process describes how Earth's crust is rising a few cm per year in Scandinavia and Canada as it has been relieved of the weight of thick ice sheets since the last Ice Age, when the heavy load caused the crust to depress. In connection to this there is a global redistribution of water in the oceans as a consequence of past and present ice melt with typical effects of fall of sea level close to the location of the original ice caps and rise further away. A better understanding of these processes helps assessing the potential dangers of present-day sea-level change.



Ocean dynamic topography variations with respect to the latest geoid (CLS)

The first Earth Explorer core mission

The GOCE mission concept was first proposed and considered at the first Living Planet Programme User Consultation Workshop held in Granada, Spain in May 1996, along with eight other candidates. The measurement principles exploited by GOCE already had a long history and the concept was conceived in large part in prior preparatory studies for the Solid Earth Science and Application Mission for Europe (SESAME) in the 1980s, and subsequently the ESA Aristoteles mission concept.

On completion of the 1996 Granada Workshop, recommendations for four missions were made by the ESA Earth Science Advisory Committee (ESAC) from the nine candidates. The Earth Observation Programme Board (PB-EO) subsequently considered the ESAC recommendations and endorsed the selection of GOCE for study.

A Mission Advisory Group (MAG) was established to support ESA with advice during pre-Phase A concept assessment studies, and to oversee supporting scientific studies. The MAG members were tasked with establishing scientifically driven performance requirements in the form of a mission requirements document. In July 1998, a Phase A design feasibility study was initiated with industry on the basis of the resulting system requirements.

At the end of this study in July 1999, a final Report for Mission Selection (ESA, 1999) was drafted and presented at the second User Consultation Workshop in Granada, Spain in October 1999. GOCE was one of two core Explorer missions to be recommended by ESAC for selection. The PB-EO subsequently endorsed the ESAC recommendation in November 1999 and authorised ESA's proposal to begin GOCE implementation as the first Earth Explorer mission.

Ocean Circulation

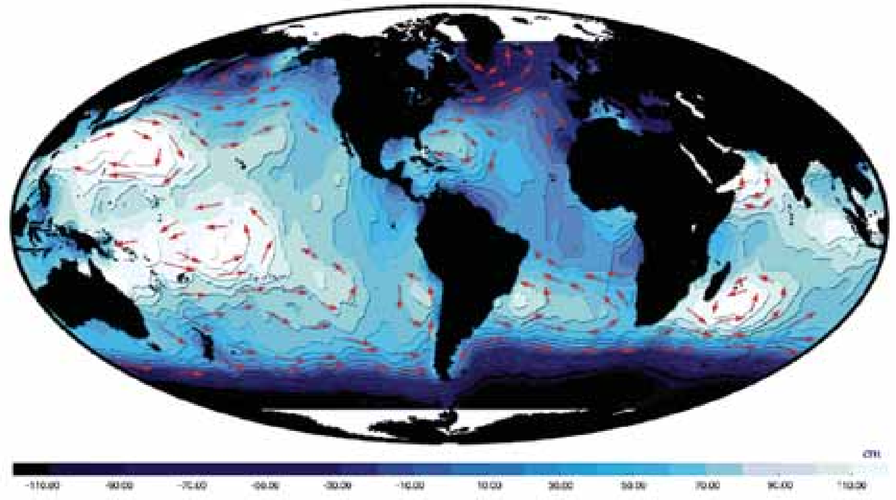
The geoid surface mapped by GOCE will provide a global reference surface for oceanography applications. The geoid represents the shape that the ocean surface would take in response to variations in Earth's gravity, were the ocean to be motionless. Ocean currents cause gradients and topographic variations in the ocean surface that can be measured by existing ESA ocean altimeter systems such as RA on ERS-2, RA2 on board Envisat, or the future GMES Sentinel-3 SRAL. It is therefore the combination of sea-surface topographic mapping by altimeters and the precise ocean geoid that give access to essential details of the ocean circulation patterns at length scales of 100 km.

Mean sea-surface heights (cm) measured by altimeter systems are accumulated and converted to topography by expressing the ocean surface variations relative to the geoid. Variations in sea-surface topography are typically between –1 m (deep blue) and +1 m (light blue) relative to the geoid. This sea-surface shape, known as the dynamic topography, is related to large-scale ocean currents and is characterised by prominent regional variations expressed in the form of elevations and depressions.

Importantly, the large-scale current systems flow along the lines of equal topography and are focused around the strongest gradients in sea-surface height. In the northern hemisphere, the flow is clockwise around elevated ocean surface regions, due to the well-known Coriolis effect caused by the rotation of Earth. In the southern hemisphere, the flow is counter-clockwise around high elevations. Global maps of the dynamic topography reveal the primary features of the general circulation. Ocean gyres and associated major currents are highlighted, as is the major Antarctic Circumpolar Current which links together all of the major ocean basins in the southern hemisphere.

One of the main benefits of having access to a 1–2 cm geoid is that the variability in the ocean currents may be characterised in conjunction with either existing or future altimetry data. The world's oceans exhibit many movements and variations which are more vigorous in some regions than in others. The strongest currents are observed near the western seaboard of the oceans, such as the Gulf Stream in the North Atlantic, the Malvinas Current in the South Atlantic, the Kuroshio Current near Japan and the Agulhas Current in the Indian Ocean south of Madagascar. These are also are the zones in the ocean where the strongest transports of heat and salt are exhibited.

Presently, the degree to which altimetry data can be used to make precise estimates of the transport of heat, salt and freshwater, is limited by



Large-scale patterns in ocean currents (red arrows) in relation to dynamic topography as observed by satellite altimetry (CLS)

Gravity missions in a wider context

Starting in 2000, satellite gravity field recovery entered the international 'geopotential decade' with the launch of a series of three complementary missions dedicated to gravity field recovery. These missions are CHAMP, GRACE and GOCE.

CHAMP

The CHAMP satellite mission was launched in July 2000. It combines gravity field determination with magnetic field measurements and atmospheric sounding. For the gravity field, CHAMP is equipped with a GPS positioning system and micro-accelerometer at its centre of mass. Together these instruments allow gravity derivation from continuous three-dimensional tracking of the spacecraft relative to GNSS satellites, and 3D accelerometer measurement of the non-gravitational forces on the satellite. CHAMP is descending slowly from an initial altitude of 454 km and its data over time have significantly contributed to improving our knowledge of the characteristics of the static gravity field at larger scales by providing homogeneous sampling and quality and by covering the polar regions. The mission has exceeded its nominal mission lifetime of five years, and continues to acquire good quality data.

GRACE

The GRACE twin-satellite mission was launched in March 2002. GRACE has the objective of determining temporal variations (i.e. on monthly, seasonal and interannual timescales) in Earth's gravity field, together with further refinement of the static component at medium spatial scales. It uses two identical satellites in the same orbit separated by approximately 220 km. The relative motion and distance between the two satellites is measured with a precision K-band microwave ranging radar system. Meanwhile, each satellite is equipped with a GPS positioning system and a micro-accelerometer at its centre of mass, allowing continuous 3D tracking of the spacecraft relative to GNSS satellites and 3D accelerometer measurement of the non-gravitational forces on each of the satellites. The GRACE system has been tailored successfully to obtain best possible measurement precision at large and medium spatial scales, in order to be able to recover time-variable gravitational signals.

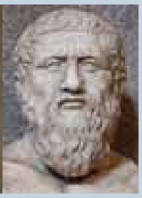
Short History of Knowledge of Earth's Gravity

2nd century BC – 2nd century AD

The first rudimentary model of our Universe was constructed between the Greeks Aristotle and Plato, and Ptolemy. This early model contained the movements of the planets in relation to star locations, together with the motions that the Sun and Moon appear to trace around Earth. Ptolemy collected these ideas and formulated a series of circles or 'epicycles' that characterised the movements of the planets around Earth.

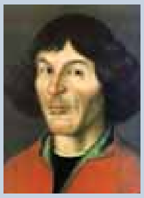

Ptolemy


Aristotle


Plato

16th century

Nicolaus Copernicus succeeded in greatly simplifying the concepts of Ptolemy, putting the Sun in its rightful place at the centre of the Solar System, but few appreciated the value of his work until after his death.


Copernicus

17th century

A combination of the ideas of astronomer Tycho Brahe and mathematician Johannes Kepler led to a breakthrough. Their collaboration led to a description of the orbits of the planets around the Sun, including the notion that the orbits need not be perfectly circular. The age of planetary orbital theory had begun.


Brahe


Kepler

1638

During the mid 17th century, the physicist Galileo Galilei unwittingly began to work on the opposite side of the same problem, gravity. By conducting experiments describing the Earthly effects of gravity on objects falling from a tower, Galileo was able to formulate theories describing the results and publishing his book *Two New Sciences*.


Galilei

Late 17th century

With supposed inspiration from a falling apple, physicist Isaac Newton finally unified the theories of planetary motion and an understanding of the force of gravity with his description of the laws of motion. He understood that there was a force that was pulling heavy objects towards the centre of Earth and that the magnitude of this force depended on the distance from the centre. Through conversations with colleagues Hooke and Halley, Newton was able, together with the aid of Keplers' ideas about planetary motion around the Sun, to formulate an inverse square law that causes a body to move on an ellipse around the Sun. He wrote a document '*On the Motion of Bodies in Orbit'* in which he defined quantity of matter as mass, and quantity of motion as the product of velocity and mass.

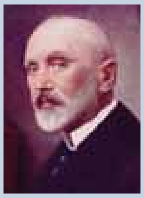

Newton

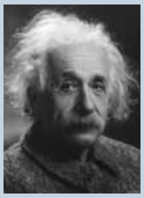
1686

Newton wrote his first volume of the book *Philosophie Naturalis Principia Mathematica* in which he established that there is a force of attraction between masses called gravity. Newton for the first time established relationships between the forces acting on a body and the motion of the body. Today these laws form the basis for classical mechanics and are used to explain many results concerning the motion of physical objects. In his third volume, he showed that these laws of motion, combined with his law of universal gravitation, explained Kepler's laws of planetary motion.

Early 20th century

Hungarian physicist Loránd Eötvös, inspired by Newton's work, studied the gravitational gradient on the surface of Earth. An instrument, called torsion balance, was developed to measure local effects of the spatial changes in gravity field. His idea has been an inspiration for proposing airborne and satellite gravity gradient measurement concepts since the late 1960s and even Einstein cited Eötvös' work on weak equivalence principles in his 1916 *The Foundation of the General Theory of Relativity.* To exploit Einstein's ideas for gravity field determination from space would require further advances in technology. Newton's theory, together with Eötvös work on gravity gradients, form the basic concepts used in the satellite mission GOCE for mapping the gravity field of Earth.


Eötvös


Einstein

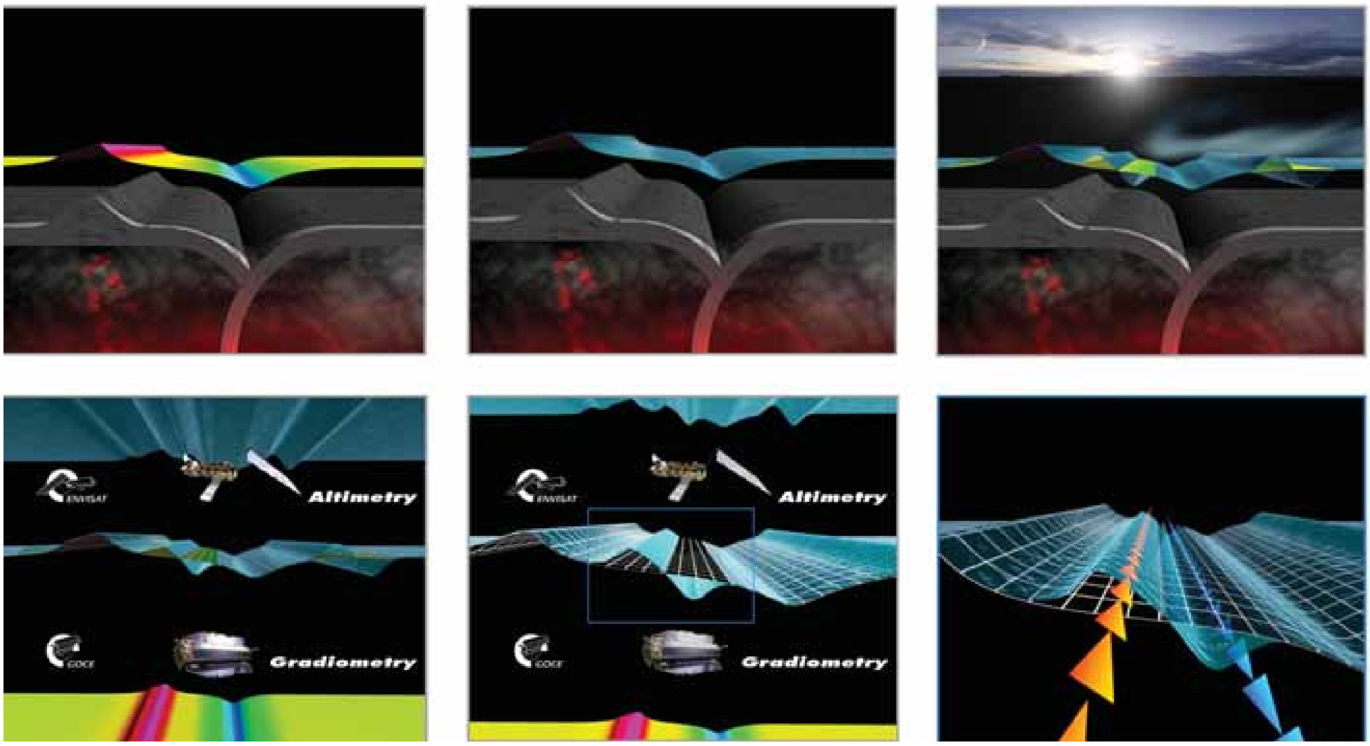
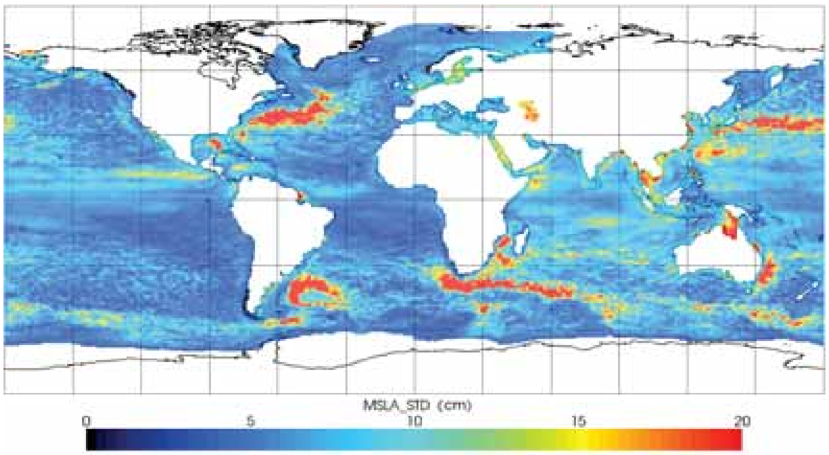


Illustration of (left to right, upper row): gravity field anomalies in response to crustal and interior density variations; the geoid or surface representing the ocean at rest; dynamic topography forced by winds and temperature variations. Lower row (left to right), the respective elements of the system measured by the altimeter missions and the GOCE mission; in central and right panels, the enlarged difference between the geoid grid and the altimeter-measured ocean topography gives access to information about ocean currents (AOES Medialab)



Standard deviation computed from 12 years of altimetry data (all available satellites during the 1992–2004 period) (Aviso)

the quality of the geoid at short length scales. In order to properly measure these transports, the strong sea-surface gradients and the sea-surface height variations, caused by eddies or vortices generated by instabilities, must be properly captured. Height variations in the vicinity of these currents, caused by eddies tens or hundreds of kilometres across, can be as much as 0.3 m.

The Antarctic Circumpolar Current is another highly energetic current unbounded by any continent across which there is a significant gradient in ocean topography. Our present estimates of the extent to which it participates in transporting and exchanging water masses around the globe is similarly limited by the knowledge of the details of the geoid.

Given the exciting possibility of the new 1–2 cm geoid from GOCE, global satellite altimetry data records spanning the last 15 years can be used to provide a detailed retrospective picture of these ocean variations, and their consequences for the global freshwater and energy cycles.

Summary

The GOCE Earth Explorer mission is poised to open a new chapter in the pursuit of a greater understanding of Earth's gravity. Perhaps most importantly, the succession between CHAMP, GRACE and GOCE gravity missions in this geopotential decade will lead to many benefits in terms of their significant cumulative and combined contributions to Earth system sciences. GOCE nonetheless represents a unique scientific contribution in this succession, striving for ultimate performance in an orbit previously untried by ESA Earth observation missions.